Heat Capacity and Thermal Conductance Measurements of a Superconducting/Normal Mixed State by Detection of Single 3 eV Photons in a Magnetic Penetration Thermometer

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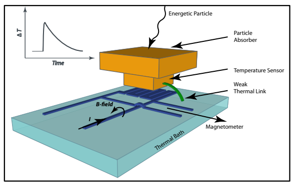
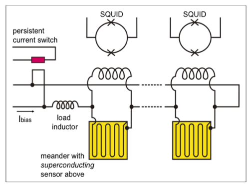
MPT operation



Cartoon of self-inductance MPT

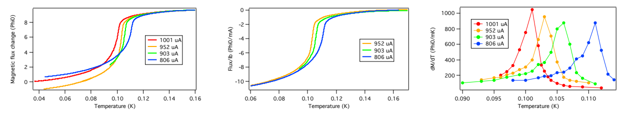


MPT circuit diagram

- A persistent current is trapped in the bias circuit above the T_c of aluminum wirebonds that connect each sensor to its associated SQUID.
- As we cool or warm through the MoAu sensor's superconducting transition, the inductance of the meander changes as the MoAu film expels or allows entry of flux, and we measure a current proportional to the sensor's magnetic response.
- *MPTs give us a unique avenue to probe superconducting effects in MoAu films.*

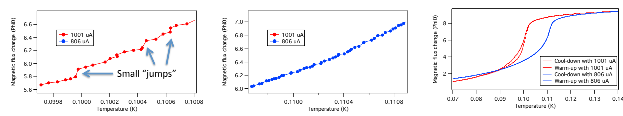
M vs *T*

- Four different bias currents (806 uA, 903 uA, 952 uA, 1001 uA)



M vs *T* curves at four bias currents | Flux change normalized by bias | Corresponding d*M*/d*T*'s

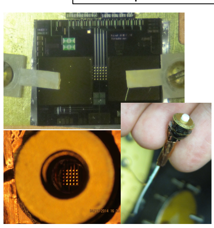
More jumps and more hysteresis at higher currents



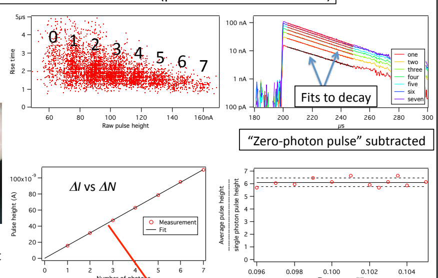
C and G Measurements

1. Using 3-eV photons from a Blu-ray diode

An example data set at 1001 uA and 100 mK (photon number resolved)

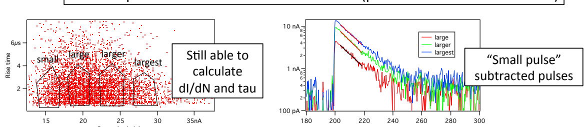


- 405 nm (3.06 eV) photons from a Blu-ray diode outside the cryostat
- Photon pulse width: 0.7 us, repetition rate: 70 Hz
- 10,000 triggered records at each T

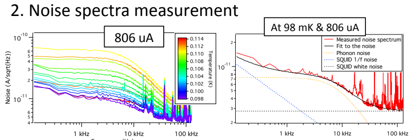


$$C=\frac{E_\gamma}{\Delta T/\Delta N}=\frac{E_\gamma}{(\Delta I/\Delta N)/(\mathrm{d}I/\mathrm{d}T)},\quad G=C/\tau$$

An example data set at 1001 uA and 109 mK (photon number not resolved)



2. Noise spectra measurement

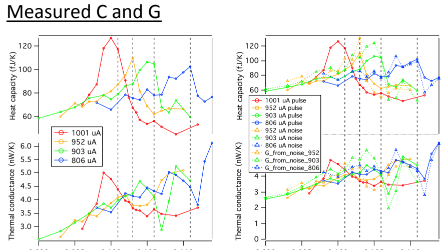


1000 noise records averaged at each temperature

$$\frac{\text{Phonon noise }[\mathrm{A}/\sqrt{\mathrm{Hz}}]}{\mathrm{d}I/\mathrm{d}T}=\sqrt{\frac{4k_{\mathrm{B}}T^2}{G}\frac{1}{1+(f/f_c)^2}}$$

⇨ $\boxed{G,\ \tau}$ ⇨ $\boxed{C=\tau G}$

Measured C and G

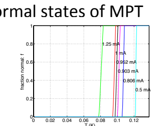


- Measured C and G using 3-eV photon data only (*left*) and together with noise spectrum data (*right*)
- The two methods share the same $\mathrm{d}I/\mathrm{d}N$ and τ values

Theory

1. Free-energy difference between superconducting and normal states of MPT

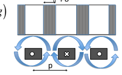
- f = fraction of meander length for which MoAu enters a partly-normal intermediate state
- g = fractional width of normal stripes in intermediate state region
- ζ = superconducting energy gap reduction in Ginzburg-Landau equation
- Solve to find state with minimum free energy of MPT relative to fully normal state. Free energy contains inductive and condensation terms:

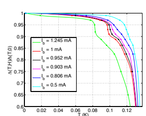

Plot of $f(T)$. Meissner transition varies with bias.

$$G_s-G_n=\frac{1}{2}I_b^2\frac{\left[L_m(\infty)+L_i\right]\left[L_m(\infty)-L_m(T)\right]}{L_m(T)+L_i}-\frac{B_c^2(T)}{2\mu_0}\left(s^2d\right)\left(1-fg\right)\left(2\zeta^2-\zeta^4\right)$$

$$L_m(T)=L_m(T,f,g,\zeta)=(1-f)L_L\left(\lambda_{BCS}(T,g,\zeta),0\right)+fL_L\left(\lambda_{BCS}(T,g,\zeta),g\right)$$

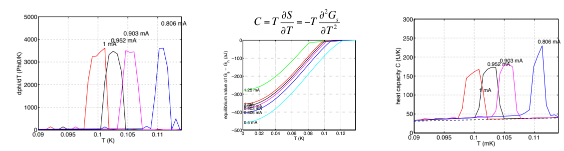
$$B_c(T)=B_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right],\qquad B_c(0)=571\ \mu\mathrm{T},\qquad \zeta=\frac{\Delta(T,H)}{\Delta(T,0)}$$




Plot of $\zeta(T)$.

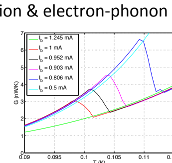
2. Heat capacity from second derivative of free energy

$$C=T\frac{\partial S}{\partial T}=-T\frac{\partial^2G_s}{\partial T^2}$$



3. Thermal conductance: quasiparticle recombination & electron-phonon cooling

- In superconducting regions, recombination of quasiparticles into Cooper pairs should be dominant cooling mechanism.
- In normal regions, quasiparticles cool by only phonon emission.
- We estimated Kaplan's τ_0 and Wellstood's Σ from the electronic and mechanical parameters for Mo and Au. A priori values fit G data within one order of magnitude.
- Fit results: τ_0 = 56 μs, Σ = 1.1x10^9 W/(K^{5}m^3).



Conclusions

- We measured the variation in heat capacity and thermal conductance of a molybdenum-gold Magnetic Penetration Thermometer (MPT) near its field dependent Meissner transition temperature.
- We did this by two methods: detection of pulses in response to absorption of one or more 3 eV photons, and equilibrium noise measurements.
- Observed *C* & *G* show peaks in approximate agreement with a Ginzburg-Landau model of the superconducting intermediate state of an MPT.

References

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- "Superconducting Effects in Optimization of Magnetic Penetration Thermometers for X-ray Microcalorimeters," T.R. Stevenson et al. IEEE Trans. Applied Superconductivity 23:2300605 (2013).
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